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NOTES ON GEOLOGICAL MAP-READING.

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PREFACE.

Map-reading, to which the student of Geology should be introduced at an early stage of his training, lends itself, by the use of contoured geological maps, to methods of precision. These are here reduced to the simplest terms by the device of reckoning slopes and dips as gradients. Trigonometrical calculation is thus avoided, the protractor becomes unnecessary, and all questions are solved by the scale alone.

It will be understood that teaching is to be illustrated by examples, and these may be easily constructed on the lines of the following pages.

September, 1920.

I. TOPOGRAPHICAL MAPS

(1) A geological map is an ordinary topographical map with additional indications (boundary-lines, colours, symbols) designed to show the geological constitution and structure of the country. The geological information so presented cannot be adequately realised without constant and instinctive reference to the form of the land-surface on which the various rocks are exposed. It is therefore of the first importance to be able to *read* a topographical map readily; *i.e.* to interpret at a glance the general character and details of the surface-relief as there rendered. We shall accordingly begin with some remarks under this head.

(2) Since the earth has a curved surface, in the simplest view spherical, while a map is flat, the former or any portion of it cannot be truly depicted on the latter (apart from reduction of scale), but can only be *represented* according to some particular convention. Numerous different modes of effecting this (different kinds of "projection") have been devised by map-makers, but they need not be described here. Either there must be some distortion (*i.e.* the linear scale is not the same for N.-S. distances as for E.-W.), or if this be avoided, as in Mercator's projection, the areal scale must be different in different parts of the map. The methods in common use are of the nature of compromises, and for a small area the question is not of great importance. Note, however, that on an ordinary map the meridian lines, except the central one, are not parallel to the sides of the rectangular sheet, but (for northern latitudes, converge northward, while the parallels of latitude are curved. The sheets of our Ordnance Survey are not to be regarded as complete maps. The small-scale sheets are parts of a large map of England (or Scotland or Ireland) drawn to the central meridian of the country. The large-scale sheets are each part of a county map drawn to the central meridian of the county.

GEOLOGICAL MAP-READING

(3) The *scale of reduction* of a map is expressed either as a fraction or ratio, such as 1 : 50,000, or more usually in English by the number of inches (or fraction of an inch) representing one mile. The two scales most in use for the Ordnance Survey of this country are : (i.) one inch to a mile, equivalent to 1 : 63,360, and (ii.) six inches to a mile, equivalent to 1 : 10,560. The latter scale is that adopted in most of the illustrations given below. Each published sheet is provided with an engraved scale of feet in the margin ; but the student will require a movable scale of ivory or boxwood, which can be applied directly to the map. The usual form is combined with a *protractor* for measuring and laying off angles. Most convenient is a scale of six inches to the mile graduated in feet. If this is not procurable, a good substitute is a scale, made for use in the Army, at two inches to a mile and graduated in yards ; if the yards be read as feet, this becomes a scale of six inches to the mile.

(4) A careful draughtsman may construct scales for himself as follows. On a sheet of cardboard, with a fine-pointed pencil, rule twelve horizontal lines at equal intervals, starting from a vertical line on the left. Divide the top line, beginning at the left, into eighths of an inch, each division, therefore, representing 110 feet. From each dividing point rule a line to the left end of the bottom line. Each horizontal line is now divided into equal parts by the radiating lines. The value of one division, being 110 feet for the first line, is 100 feet for the second, 90 for the third, and so on. The most useful scales are those for 100, 50, and 20, or a scale of 25 can be made by ruling a new line midway between the ninth and tenth. Ink in the desired scales, and cut along the horizontal lines.

(5) Any land-surface, apart from the curvature of the globe, is diversified by hill and valley, and so is in three dimensions. A map has only two dimensions, and therefore the third (*viz.* altitude) cannot be directly rendered, but only indicated (and that imperfectly) by some convention. Hill-shading as a mode of rendering surface-

relief lacks the element of precision, and we shall use the alternative method of *contour-lines*. Any horizontal plane intersecting the surface of the ground gives a curve of intersection which is a contour-line of that surface; and a series of such curves, taken at equal vertical intervals sufficiently close, affords a representation of the shape of the surface. We shall take contour-lines at intervals of

FIG. 1.

100 feet, beginning from sea-level.* Imagine the sea to flood the land by a rise first of 100 ft., then of 200 ft., 300 ft., etc. (fig. 1). The successive shore-lines will be contour-lines on the ground, and the *projection* of these on a horizontal plane, with reduction on the proper scale, will give the contour-lines on the map.

(6) A contoured map, then, when rightly interpreted, gives a picture of the shape of the ground represented. The slope at any

* On the maps of the Ordnance Survey the vertical interval is usually 100 ft. up to 1000 ft. altitude and 250 ft. above that. There is also a line for 50 ft. altitude.

place is in the direction at right angles to the contour-lines, from higher to lower. The relative closeness of the contour-lines indicates the relative steepness of the slope. If as we pass uphill the lines become closer, the slope is becoming steeper, and the curve is a concave one; if the lines become more open, the slope is becoming

FIG. 2.

FIG. 3.

gentler, and the curve is convex. The student should observe on actual contoured maps the characteristic features of land-forms—the closed curves about an isolated hill, the indentation of the lines in crossing a valley, the distinctive appearances of a lake-basin, a pass, a cliff, an escarpment, etc.—until he can read the map as easily as a raised model. In the figures appended as illustrations the most southerly contour-line is to be taken as the lowest, and the vertical

interval is supposed to be 100 ft. Fig. 2 represents a ridge somewhat over 300 ft. high dying out southward into level ground ; fig. 3 a country sloping southward, intersected by a gorge 250 ft. deep, with a waterfall at its head ; fig. 4 a round hill rising over 800 ft. from a country with a southerly slope (observe the pass on the north side).

FIG. 4.

(7) The inclination of a slope can be measured and expressed in two ways : (i.) as an *angle* measured in degrees, *viz.* the angle which the surface makes with the horizontal, and (ii.) as a *gradient*. We shall employ by preference the latter method, but the two measures are mutually convertible by means of the table given at the end of the book. If, in fig. 5, *ac* measures one unit (of any length) and *bc* four units, the gradient along *ab* is 1 in 4. Here 4

is simply the co-tangent of the angle of inclination, which is very closely 14° . A gradient 1 in 4 is the same as 10 in 40, or 100 in 400, and we shall find this last measure most suitable for our purposes.

(8) To *determine the slope* of the ground at any place on a contoured map (fig. 6), apply the scale so as to read off the distance ab between consecutive contour-lines, say 400 ft. Then the slope has a gradient 100 in 400, equivalent to 14° inclination. Since the slope is probably not constant, this is really the average slope between the two contour-lines at this place. Taken thus, at right angles to the contour-lines, it is the steepest slope there. To determine the slope in any other direction such as ap , we have only to measure ap , say 950 ft., and the slope in that direction is

100 in 950 (about 6° by the table). This holds good whether the contour-lines be straight or curved.

(9) To draw a *profile section* along a given line on a contoured map, *i.e.* the section made by a vertical plane along that line.* Lay down the line on the map (fig. 7), apply the straight edge of a strip of paper to it, and mark there where it crosses the several contour-lines, as also the point where it crosses a stream. The altitude for this point can be roughly fixed by observing where contour-lines cross the stream above and below the point and assuming a steady gradient for the stream-bed. Transfer these data to the ruled base-

* Styled very laxly by the Geological Survey a "horizontal section."

FIG. 7.

line (representing sea-level) on the drawing-sheet; erect perpendiculars of the proper heights at the marked points; and draw a

curve through the summits of the perpendiculars. Ink in the curve and erase the pencil marks. Indicate the direction of the section by noting the points of the compass at the opposite ends. It is a convenience to have the drawing-sheet previously ruled with horizontal lines marking altitudes at 100 ft. intervals, as in fig. 26 on next page.

II. STRATA WITH CONSTANT STRIKE AND DIP

(10) We can now go on to consider a *geological map*, assuming it to have as its basis a topographical map with contour-lines. We shall be concerned mainly with stratified rocks, and in particular with those groups of strata which are separately distinguished on the map by colouring or otherwise, to be called for clearness *formations*. What the map primarily shows is the distribution of these formations as they appear at their *outcrop* on the ground-surface. The most important geological lines on the map are the boundaries separating the several formations, and each such line represents the outcrop of a particular bedding-surface in the rocks, *viz.* the summit of one formation and the base of the succeeding one. This surface is intersected by the ground-surface in a certain curved line in space, and the projection of this curve on the horizontal plane is the boundary as shown on the map. It is determined, therefore, by two factors; the lie of the bedding and the shape of the ground. Given the shape of the ground (say by contour-lines) and the lie of the bedding at every place, the course of the boundary lines could be inferred. In map-reading it is the converse problem that is presented; given the shape of the ground and the (projected) boundary-lines, to make out the lie of the bedding, which may vary from place to place.

(11) In the special case of *horizontal bedding* the distribution of the several formations depends solely on the shape of the ground, the lowest appearing in the valleys and the highest on the hill-tops. Horizontal bedding is easily detected on the map, since in this case all the boundary-lines are contour-lines, and must conform with the regular system of contour-lines marked on the map. More generally the bedding at any place has a *dip* in a certain direction and of a

certain amount. The manner of denoting this on the map is by a small arrow (its point at the spot in question) with a number indicating the inclination in degrees. Horizontal bedding is denoted by the sign +. The *strike* of inclined strata is often defined as the horizontal direction at right angles to the direction of dip. Strike is, however, a more fundamental conception than dip. We shall accordingly define a *strike-line* as a horizontal line drawn on a bedding-surface, or (what is the same thing) the line of intersection of a bedding-surface by a horizontal plane. A strike-line on a bedding-surface is therefore precisely analogous to a contour-line on the ground-surface, and this is the best way of realising its significance. The dip of the bedding is analogous to the slope of the ground, and is to be expressed in the same manner, preferably as a gradient (§ 7). The "dip," without qualification, is understood to mean the dip in a direction at right angles to the strike. This is the steepest dip at a given place, and the dip in any other direction is related to it in the manner shown for slopes in § 8.

(12) In reading a geological map the first thing is to *determine the strike* of the bedding, and only after that the direction and amount of dip, which are much more likely to be variable. A glance at a map with average surface-relief shows whether we have to do with low or with high dips. With low dips the form of the ground is the chief factor in determining the course of an outcrop, and the boundary-lines are accordingly sinuous; with high dips the lines tend to run in a definite direction, which is that of strike. In any case, if a line declines when followed in one direction (*i.e.* approaches a lower contour-line), there must be some dip in that direction. If it declines rapidly in one part of its course and only gradually in another part, the former direction must be nearer that of true dip and the latter nearer that of strike. If a boundary-line runs for some distance closely parallel to a contour-line, there is no sensible dip in that direction, or in other words it is approximately the direction of strike. When a boundary-line cuts the same contour-

line twice, we can lay down the strike with precision by joining the two points of intersection, since a horizontal line on a given bedding-plane is by definition a strike-line. Observe that we are here assuming the bedding-surface to be an inclined plane: folded bedding will be discussed later.

(13) It is necessary to consider more closely the *course of outcrop* of a bedding-surface as depending on the strike and dip and on the shape of the ground. We will suppose these constant, so that both bedding-surface and ground-surface are inclined planes. The

outcrop, which is the intersection of these two planes, is then a straight line, and so is its projection on the horizontal plane. If the dip is directly up or down hill, or (in other words) if strike and contour-lines are parallel, the outcrop will be parallel to both. If, however, the strike is not parallel to the contour-lines, the outcrop will take a direction different from both. This will be clear from fig. 8, remembering that it is the projection upon the horizontal of a figure in three dimensions. Suppose the slope of the ground to be

100 in 1000, and the dip to be obliquely downhill at the steeper gradient of 100 in 600. Let p be a point on the outcrop of a particular bedding-plane at an altitude, say, of 400 ft., and pa the contour-line of the hill at this level. Draw also, 1000 ft. in front of this, the contour-line for the 300 ft. level. In like manner, let pb be the strike-line through p , *i.e.* at the 400 ft. level, and draw, 600 ft. in front of it, the strike-line at the 300 ft. level. The latter line will meet the contour-line at the same level in a point q , which is clearly a point on the outcrop, and pq is therefore the line of outcrop. In fig. 9, with corresponding lettering, the intersection of the two inclined planes is shown in perspective. Note that p, a, b are in one horizontal plane (at 400 ft.), and q, c, d in another horizontal plane (at 300 ft.).

(14) We now see how to *measure the dip when the strike is known*. Suppose a boundary-line (representing a certain bedding-plane) to cross two consecutive contour-lines at p and q (fig. 8). Draw strike-lines through these two points, and measure the distance between them (600 ft.). Then the bedding-plane declines 100 ft. in this distance, and its dip is therefore at 100 in 600 (about $9\frac{1}{2}^\circ$) in the direction pd . If in a given part of the map there is no boundary-line which crosses two consecutive contour-lines, we must be content to measure the distance in which there is a decline of, say, 50 ft. or 25 ft. This involves interpolating altitudes between the contour-lines, which gives a sufficiently approximate result upon a steady slope.

(15) The student should construct diagrams like fig. 8 to observe the effect of different slopes and dips. (i.) In the case illustrated the line of strike lies between the contour-line and the outcrop. (ii.) If, however, the slope is steeper than the dip (downhill), the outcrop deviates in the opposite direction, and falls between the contour-line and the strike-line. (iii.) This is likewise true if dip and slope are opposed. (iv.) In all cases the deviation of outcrop from strike is greater according as the dip is lower or the slope is

FIG. 10.

steeper. Note also the extreme cases: for vertical bedding the outcrop is parallel to the strike, for horizontal bedding to the contour-line. On level ground the outcrop is parallel to the strike, whatever be the dip.

(16) Still supposing the bedding to maintain a constant strike and dip, we can now follow the outcrop of a bedding-plane on ground of varying slope. We see that in general it must curve forward (towards the direction of dip) on falling ground and backward on rising ground, the only exception being when the dip (downhill) is less steep than the slope. The effect is clearly seen where an outcrop crosses a pronounced valley, and so makes a sharp deviation and recovery, the indentation being conveniently spoken of as a V. This is illustrated for three different cases in fig. 10, in which contour-lines are shown for vertical intervals of 100 ft., and the stream-line of the valley declines at a gradient of 100 in 1000. In the first case (A) the dip is downstream at 100 in 500. If a bedding-plane crosses a contour-line at the two points *a* and *b*, then *ab* is a strike-line. Drawing another strike-line 500 ft. in front of this, we see that the points *c* and *d*, in which it intersects the next lower contour-line, must also be points on the outcrop. By proceeding in this way the curve or V is traced out. In B is shown the exceptional case in which the dip, still downstream, is less steep than the gradient of the stream-line, and the V points upstream instead of down. Case C shows the dip upstream and the V pointing upstream accordingly. Observe (comparing C with A) that the V is blunter here than for an equal dip downstream.

(17) In an area too small to afford a general view of the relations, the following method may be applied with caution for determining strike and dip. A plane is fixed by any three points in it which make a triangle (*i.e.* are not in one straight line). If, then, strike and dip can be supposed constant, it is sufficient to know the altitudes of three points on one boundary-line. In fig. 11 three points, *a*, *b*, *c*, are given by the intersections of three contour-lines.

Since a is at 400 ft. altitude and c at 200, the point d midway between them in the same inclined plane (*i.e.* a point in midair, not on the ground-surface) is at 300. This is at the same altitude as b , and db

FIG. 11.

is therefore a line of strike. The dip is in the direction ae , perpendicular to db , and is at the rate of 100 in 1200 (1200 being the measure of ae). [*Ex.* Make a like construction for the other outcrop shown.] This method is of little value for a triangle of narrow shape.

(18) In general, the outcrops of the several formations follow one another on the map as belts of varying width, younger forma-

FIG. 12.

tions coming on as we pass in the direction of dip. The *order of superposition* is therefore easily made out, and should be tabulated at the outset. There may be, however, an isolated area of one formation entirely surrounded by younger (making an *inlier*) or by older (an *outlier*). In strata with constant dip an inlier must be very exceptional. It can occur only in the bottom of a valley where the valley-gradient is first steeper and then less steep than the downstream dip. An outlier may occur on any hill, provided that some part of the slope, on the dip side of the hill, is steeper than the dip. This is illustrated in fig. 12, where the dip as shown is eastward at 100 in 750. Beginning with the outcrop *ab*, we can

FIG. 13.

follow its course eastward and downhill by the method of fig. 10. The line *ab* is a strike-line at 500 ft. altitude. A parallel line 750 ft. in front of this meets the 400 ft. contour-line in *c* and *d*, which are therefore points on the same outcrop; and so on for successive levels. If now we start with the outcrop *kl*, we obtain in the same way the points *m* and *n*, *o* and *p*; but the next strike-line *qr* does not meet the corresponding (300 ft.) contour-line, and the outcrop must therefore make a closed curve as drawn. Note, however, that the next succeeding strike-line does meet the 200 ft. contour-line in points *s* and *t*, which are on the main outcrop to which the outlier belongs. This will be more evident with the aid of fig. 13, which is a W.-E. section through the hill. [This and the following maps, all on the scale of six inches to a mile, should be carefully studied. They will be made clearer by adding a thin wash of water-colours.]

(19) The *width of outcrop* of any formation is, of course, proportional to its thickness, but depends also upon the dip and upon the slope of the ground. The width as measured on the map is equal to the thickness only when the bedding is vertical. With low dips the width is in general considerably greater than the thickness, unless the beds crop out on a steep escarpment or cliff. If in some place dip and slope coincide, a single bed (of some resistant rock) may be exposed over a wide belt, making a "dip-slope." As regards thickness, we have to distinguish between the *true thickness*, measured perpendicularly to the bedding (bc in fig. 15) and the *vertical thickness* (bd). To obtain the former from the latter,

FIG. 14.

FIG. 15.

we must multiply by the cosine of the angle of dip. The table shows that this correction is negligible for low dips, and does not amount to a difference of 5 per cent. until the dip reaches 18° .

(20) To *measure the vertical thickness* of a formation from the map. For horizontal bedding (fig. 14) the vertical (and also the true) thickness is merely the difference of altitude between a and b , points on the lower and upper boundaries. For inclined bedding outcropping on level ground (fig. 15) the vertical thickness bd is merely the amount which the base declines in a horizontal distance ab , and can be calculated directly from the known gradient of dip. In the more general case (fig. 16) we have to reckon with both slope and dip. We have to determine therefore both be , the difference of altitude between a and b , and de , the amount by which the base

declines in the distance ae (measured on the map). The vertical thickness is then the difference or the sum of these in different cases :

(A) Dip steeper than slope,

$$bd = de - be.$$

(B) Slope steeper than dip,

$$bd = be - de.$$

(C) Dip opposed to slope,

$$bd = be + de.$$

FIG. 16.

(21) The sections in fig. 16 were taken in the direction of dip ; but we may suppose them taken in any other direction, provided that the width of outcrop, the slope, and the dip are taken as measured in that particular direction. By taking a section *along the strike* (fig. 14 will serve) we eliminate the dip, and the vertical thickness is merely the difference of altitude between a and b . This is a ready method for judging roughly by eye. To obtain the best result draw ab so that one end is on a contour-line and the other

FIG. 17

on a smooth slope where altitudes can be estimated with some accuracy. Alternatively we can eliminate the slope (fig. 15) by taking our section *along a contour-line*, or, rather, so that *a* and *b* are on the same contour-line (the form of the ground between being of no consequence). Then the vertical thickness is merely the distance through which the base declines in the horizontal distance *ab*. This method has the advantage of avoiding any judging of altitude between the contour-lines.

(22) For illustration we will estimate the vertical thickness of the formation D in fig. 17. The dip is seen to be constant at 100 in 1200 in a direction nearly E. 30° S. (i.) By the dip method of § 20. Draw the line *ab* across the outcrop in the direction of dip, and measure it (1300 ft.). In this distance the base of D declines (at the known rate of dip) 108 ft. Since *a* is about 25 ft. higher than *b*, we must subtract this figure, and we obtain 83 ft. for the vertical thickness. (ii.) By the strike method of § 21. Draw *bc* across the outcrop in the direction of strike. The altitude of *c* may be judged at about 315 ft., while *b* is at 400, and the difference gives the vertical thickness as about 85 ft. (iii.) By the contour-line method. Take the points *d* and *e* on the two boundaries of D and on the same contour-line, and draw the strike-line *ef* and the dip-line *df*, which measures 1000 ft. In this distance the base of D declines (at the known gradient of dip) 83 ft., which is, therefore, the vertical thickness of the formation. [*Ex.* Estimate the vertical thicknesses of B, C, and E (50, 67, and 33 ft.).] Note, *e.g.* how E makes a wide spread in the north, where dip and slope are not very different, but a narrow band in the south, where the dip is into the hill.

(23) So far we have dealt with a single conformable series of formations, the product of uninterrupted deposition. Consider now the case of two distinct series, each conformable in itself, but with *unconformity* between the two, marking a discontinuity and a hiatus in the succession. The older strata have been tilted and raised above sea-level; erosion has followed, tending always towards

FIG. 18.

the establishment of "base-level"; then submergence and the deposition of a new series of strata on the eroded edges of the older. Usually the newer series has also been tilted during its elevation at a later epoch, the inclination of the older being of course modified at the same time. As now exposed there is accordingly an abrupt discordance of dip between the two series where they come together. In the most general case there is a discordance of strike also; but, unless the dips be very low, the difference of strike is not likely to be considerable. In fig. 18 we have an older series of formations, A to E, and a newer series, K to N. It is easily verified that both have in this case the same strike, and both dip westward, but the older at 100 in 400 and the newer at 100 in 750. The unconformity is most clearly perceived in the exposure of E, the uppermost member (seen) of the older series. Its eastern boundary represents its natural base, and is conformable with D below; but its western boundary is determined by a surface of erosion, which is also the base of K. Owing to its lower dip, K encroaches obliquely across E, and finally conceals it, coming to rest instead upon the underlying D.

(24) The eroded surface of the older strata, on which the newer were laid down, was not necessarily level. If it presented inequalities, these were filled in by the basal deposits of the newer series. Hence the formation immediately succeeding an unconformity often has varying thickness and irregular or inconstant distribution. In fig. 18 K exhibits a common type of such irregularity, involving *overlap*. This formation has been deposited against a gradually shelving coast to the east, so that successive beds extended farther and farther eastward, overlapping one another. In like manner K as a whole is overlapped by L; after which the sea-floor seems to have been nearly level, since L maintains a sensibly constant thickness. The effects of unconformity and overlap are to be carefully discriminated. On the map E appears to die out in the N.E. and S.E. directions, because it is covered by newer strata; but K does really die out, because it was never deposited eastward

of its present extreme exposures. [Draw sections along the lines *ab* and *cd*.] As a practical point, note that the strike and dip of an unconformable series cannot safely be determined from the behaviour of its base, but should be checked from another horizon above.

(25) We have next to examine the effects of a *fault* as shown on the geological map. A normal fault is to be conceived as a steeply inclined plane of clean fracture with relative displacement of the rocks on opposite sides of it. Those on one side have been relatively depressed through a certain vertical distance (the "throw" of the fault), but without lateral displacement parallel to the fault. We will further suppose at first that the subsidence is not accompanied by tilting, so that strike and dip are not affected. At the surface of the ground the direct effects of the displacement have been obliterated by erosion, though a fault often figures as a line of weakness marked by a depression. Primarily, a fault appears, on the ground and on the map, as a line of discontinuity, against which all boundary-lines (of rocks older than the faulting) are cut off, and are more or less shifted when resumed (if at all) upon the other side. Newer rocks on the downthrow side are brought against older on the upthrow; so that the direction of downthrow is perceived on simple inspection. The symbol to indicate it is a short line parallel to the fault with a shorter stroke at right angles to it on the downthrow side. A normal fault inclines downward towards that side ("hades towards the downthrow"), but the angle which it makes with the vertical (the "hade") is usually quite small. Consequently the fault-outcrop experiences no sensible deviation in crossing hill and valley. It may, however, have a somewhat curved course owing to actual curvature of the fault-surface.

(26) For convenience in describing their effects we may distinguish between *strike-faults* and *dip-faults*, according as their course approximates to one or the other direction. A fault making a medium angle with the strike can be regarded from either point of view. If a strike-fault, intersecting a regular succession of strata,

FIG. 19.

throws down in the direction of dip, a part of the succession will be missing in a traverse of the ground crossing the fault ; while, if the downthrow be in the opposite direction, a part will be repeated. The vertical thickness of the strata cut out or repeated is evidently equal to the throw of the fault. For a dip-fault the most noticeable effect is the shifting of the boundary-lines where they encounter the fault. The amount of lateral *shift* of any line is proportional to the throw of the fault, but depends also upon the dip and upon the slope of the ground. To realise the relation, turn to figs. 14-16, and suppose *ad* and *bf* now to represent one and the same bedding-plane on opposite sides of a dip-fault ; or for a strike-fault imagine the bedding-plane on one side produced across the fault. It is easily seen that the relation between the vertical throw of a fault and the shift which it causes is precisely the same as the relation between the vertical thickness of a formation and the width of its outcrop. The discussion in §§ 20, 21 can therefore be applied, with the necessary substitution of terms, to the case of faulting. Note that the boundary-line on the downthrow side is always shifted backward (*i.e.* in the direction opposite to that of dip), save only in the exceptional case (fig. 16, B) in which the slope is steeper than the dip.

(27) For illustration take first the *strike-fault* shown in fig. 19. Here the dip, 100 in 1125, is seen to be the same on both sides of the fault. The downthrow is north-westward, and so against the dip. Accordingly there is repetition of beds in a traverse downstream, the formation A reappearing as a " faulted inlier." To estimate the throw of the fault, consider the base of C. In the direction of dip it is shifted through a distance *ab* (1500 ft.), and the fall in this distance at the known rate of dip would be 133 ft. From this we must subtract the difference of altitude between *a* and *b*, say 50 ft., and the result is 83 ft. Next take points *a* and *c* on the same contour-line. The fall from *a* to *c* is reckoned by measuring the distance *ad* in the direction of dip (950 ft.) and using the known

FIG. 20.

gradient of dip, which gives 84 ft. To apply the strike-method, measure *ef* the shift in the direction of strike (1025 ft.), and also the distance apart of the contour-lines along *gh* (1200). The slope in that direction being 100 in 1200, 1025 ft. corresponds with a difference of altitude of about 85 ft. This last method is not here very trustworthy, and would be less so for measurements taken in the northern part of the map, where the boundaries make more acute angles with the strike.

(28) In general the dip method is better suited to a strike-fault and the strike method to a dip-fault. In fig. 20 we have a *dip-fault* throwing down to the east. The base of the formation C is about 80 ft. higher at *c* than at *a* and *b* on the same strike-line, and this gives therefore the amount of the throw. To apply the contour-line method, take the points *d* and *e*, and measure the distance *df* in the direction of dip (1050 ft.). At the rate of dip (100 in 1325) the fall in this distance is nearly 80 ft., which is therefore the throw of the fault.

III STRATA WITH CONSTANT STRIKE BUT VARYING DIP

(29) We go on to discuss strata which are not merely tilted as inclined planes, but *folded*. The strike will still be assumed constant. The dip is constant along any one strike-line, but varies in the direction across the strike, so that in a vertical section in such direction any bedding-surface appears as a curve. In any regular system of folding there are in general places where the dip changes from one direction to the opposite, passing through the horizontal. Such a place is a *syncline* or *anticline*, according as the opposed dips are towards or away from it. If we regard a particular bedding-surface, folded in wave-like fashion, we note definite lines of strike, in the arches and troughs of the folds, where the bedding is horizontal, and these, as laid down on the map, may be termed anticlinal and synclinal *axes*. When a conformable series of strata is folded together in an anticline or syncline, these particular strike-lines for the several bedding-surfaces are situated in a certain *axial plane*, which for symmetrical folding is a vertical plane. As we pass in the direction transverse to the strike, the dip is continually changing, but not always at the same rate. It changes most slowly in the middle limb of a fold, say midway between anticline and syncline, where the curve changes from convex to concave, and it is here that the steepest dip is found.

(30) It is easy to realise how the course of a boundary-line will be affected by varying dip (§ 15). Summarily, for vertical bedding outcrops run parallel to the strike; for horizontal bedding parallel to the contour-lines; for inclined bedding in an intermediate direction, nearer the strike for steeper dips and nearer the contour-lines for less steep. Fig. 21 represents an anticline, and shows the outcrop of a particular bedding-surface upon a hill-side of constant

slope. At *a*, where the dip is steep, the curve makes only a small angle with the strike, and a high angle with the contour-lines. From *a* to *b* it turns gradually away from the strike and towards the

FIG. 22.

contour-lines as the dip declines; from *b* to *c* and from *c* to *d* it turns more rapidly in the same way, as the dip declines more rapidly. At *e*, on the axis, the bedding is momentarily horizontal, and the outcrop is therefore parallel to the contour-line (touches it in the figure). Then, through *fgh*, the curve returns towards the strike

FIG. 23.

direction as the dip increases in the reverse sense. Fig. 22 is designed to illustrate this case by a view in perspective. The more general case, in which slope varies as well as dip, will present no difficulty.

(31) An area of folded strata displays its geological structure most clearly when the strike is transverse to the main lines of drainage. Fig. 23 shows an anticline and a syncline intersected transversely by a valley. The V's made by the boundary-lines point away from the anticlinal axis *aa* and towards the synclinal axis *ss*. The oldest formation A is exposed in the anticline and in the bottom of the valley, where it makes an inlier. The youngest F is exposed in the syncline and on the higher ground, making two areas which may be portions of two outliers. Note how to lay down on the map the *axes of folding*. The anticlinal axis must clearly pass between *b* and *c* where A rises highest. At some point *d* we can suppose a contour-line drawn to touch the boundary-line, and this point must be on the axis. So for *e* on the opposite side, the axis being thus fixed. This affords a good way of determining the strike. Observe that the centre of the inlier is not directly on the axis, but a little downstream; and similarly an outlier is situated a little upstream in relation to a synclinal axis.

(32) When the main lines of drainage run approximately with the folds, as in fig. 24, the structure is deciphered without difficulty, if the map is studied both as a whole and in detail. To determine the strike should be the first step. The outcrops in the valley, taken by themselves, recall fig. 10, and might suggest a downstream dip, except that *bc* and *de* (strike-lines on that supposition) are not parallel. Examined more closely, the lines (as at *ef*) indicate a strike along the valley, given more accurately by *cg*, and it then becomes apparent that there is an anticline along the valley (axis *aa*). So, too, the outcrops on the hill are to be interpreted as showing a syncline with axis *ss*, parallel to *hk* and *mn*, not an anticline with strike *hm* or *kn*. The correspondence of a valley with an anticline and a hill with a syncline is a common arrangement, a consequence

FIG. 24.

of the mechanical laws of erosion, by which slope tends to be opposed to dip. It results in a narrowing of outcrops, so that a considerable thickness of strata is exposed in a moderate width of ground.

(33) At this stage the student should review those preceding articles which deal with strata having a constant dip, and consider how far they are applicable to the more general case now in question. It is clear that all considerations involving strike alone will still hold good so long as the strike is constant. Constructions and calculations involving the rate of dip cannot in theory be applied when the dip is variable, but in practice they can often be used with judgment to obtain results very near to the truth. The general procedure for determining the strike on a map (§ 12) is still applicable; and also the particular method by joining the two points of intersection of a boundary-line and a contour-line, provided that the two points are in the same limb of a fold, not on opposite sides of an axis (*e.g.* *hk* in fig. 24, not *hm*). The method for measuring dip (§ 14), when applied to folded strata (in one limb of a fold), gives the average dip between the two strike-lines, or say the dip at midway: if the dip is changing only slowly, the measurement is as good as is needed. In fig. 23, *e.g.*, the dip of the base of D in the middle of the map is estimated at 100 in 300, which is closely the true dip (18°). Where the dip is changing rapidly, a vertical interval of 100 ft. is too great, but on a steady slope it is permissible to interpolate between the contour-lines. Thus, to find the dip at *m* (fig. 23) measure *mn* in a certain ratio to *mo*, say one-fourth, and draw through *n* a portion of a 475 ft. contour-line, meeting the boundary-line in *p*. Draw strike-lines through *m* and *p*, and measure the distance *mq* between them (150 ft.). Then along *mp* there is a fall of 25 vertical in 150 horizontal, or 100 in 600 ($9\frac{1}{2}^{\circ}$). For estimating the thickness of a formation, or the throw of a fault, the strike method (§ 21) should be used wherever it is practicable. It will give good results if the boundary-lines do not make too acute an angle with the strike (*i.e.* if the dips are not too high).

(34) In making out the character of the folding from a given geological map, lay down first the position of any anticlinal and

FIG. 25.

synclinal axes, and then determine the dip at selected points. Compare the dips at equal distances on opposite sides of an axis, to ascertain whether the folding is of symmetrical type. The most important dip to determine is the steepest one, and this, as we have seen, is the one most easily measured with accuracy. In fig. 25

we see neither anticlinal nor synclinal axis, but only part of one limb of a fold, since the dip is constantly in one direction. Evidently it is lower in the eastern than in the western part of the map. Measurements give for the average dip between *bc* and *d* 100 in 950 ; between *ef* and *g* 100 in 500 ; between *hk* and *l* again 100 in 500. We infer that *k* is situated at about the middle of the limb, where the dip is steepest, and changes only slowly.

(35) The student should constantly practice *constructing a section* from a given geological map ; not as a substitute for studying the map directly, but after such study and as illustrative of its results. The line of section should be chosen to bring out the essential structure, and its direction should be, as a rule, at right angles to the strike. In constructing a profile of the ground (§ 9) note at the same time where the line of section crosses each of the geological boundary-lines. At each such place on the profile draw a short line inwards to give approximately the correct inclination of the boundary at its outcrop. For this purpose make use of any dips marked on the map near the line of section, and estimate others as required. The boundary-lines are now to be completed as sweeping curves corresponding with the general character of the folding as already made out, giving each formation its proper thickness. If the dip at outcrop is sufficiently known, the thickness there is given by the section itself.

(36) If the strike is strictly constant, all parallel sections must be identical, except as more or less of the rocks is cut off above the ground-surface. The section should therefore be taken by preference through the higher ground, so as to utilise the data furnished by the lower ground. This can be done systematically, as in fig. 26, where the several boundary-lines are *projected upon the plane of section*. The section here is taken along the southern edge of the map, and for clearness it is shown in two stages of construction, and with a vertical scale exaggerated twofold. At *a* on the map the base of E is at 200 ft., and the same at any point along

FIG. 27.

the strike-line through *a*: this, therefore, is its altitude at the corresponding point in the section. At *b* on the map the same boundary-line is at 300 ft., which fixes another point in the section; the line *ab* in the section being simply the projection (on the vertical plane of section) of the line *ab* of the map. The point *c*, at 400 ft., belongs to the same boundary-line, but is in the opposite limb of the anticline. In like manner we can lay down on the section portions

FIG. 28.

FIG. 29.

of the base of D (*de* and *f*), the base of C (*gh*), and the base of B (*ik*); and from this skeleton the section can be filled in with considerable accuracy.

(37) In an unsymmetrical fold the axial plane is inclined, and the dips are steeper in one limb than in the other. The type of structure illustrated in fig. 27 is that known as a *monoclinal* fold. A syncline and an anticline, both unsymmetrical, occur near together. In the middle limb the dip is relatively high, as is apparent from the narrowness of the outcrops and the comparative straightness of the lines (indicating the strike at a glance). In the outer limbs the dip is low, and becomes practically constant at a distance

from the axis. [A section carefully drawn to preserve the thickness of each formation will bring out the inclination of the axial planes.]

(38) Another type is the overturned fold or *overfold*, shown in section in fig. 28, in which the strata in one limb are inverted. Except in the core of the fold (*b*) the dip has the same direction in both limbs, but is steeper in the inverted limb than in the other. In the extreme case this becomes *isoclinal* folding, in which the opposite limbs are parallel to one another and to the axial plane (fig. 29). The appearance at the outcrop is that of a regular succession of strata with steady dip; but if the individual members can be identified (by lithological characters or distinctive fossils), the repetition with *reversal of order* reveals the true relations. Note that in this closely compressed folding there is a stretching and thinning of the middle limbs with correlative thickening in the arches and troughs.

(39) Fig. 30 illustrates a tract of *overfolding*, intersected by a transverse valley. The dip is everywhere southerly. The oldest formation makes an inlier in the bottom of the valley, as in an ordinary anticline; but here the dip is in the same direction in both limbs, at a moderate angle in the southern limb and steep in the northern (overturned) limb. [Compare the heart-shaped exposure of A here with the regular shape in fig. 23, a symmetrical anticline, and the intermediate case of fig. 27, an unsymmetrical anticline.] In the northern part of the map we see the correlative infold, analogous to a syncline, but with southerly dips in both limbs, steep on the southern side and moderate on the northern.

(40) Consider next the case of two series of strata with unconformity between them and two periods of folding, the earlier folding affecting only the older series and the later folding affecting both. We suppose the strike still constant, which implies that the axes of the later folding are parallel to those of the earlier. In the *double anticline* shown in fig. 31, the axes are not merely parallel, but coincident: *i.e.* there has been elevation along the same axis *aa* at

FIG. 30.

FIG. 31.

two periods, one before and the other after the deposition of K and L. On the west side, where the outcrops spread out in accordance with the downstream dip, the discordance is evident from the transgression of the base of K across the older formations. On the east, where the dip is into the hill, it is less apparent, but is indicated by a slightly more pronounced curvature and indentation of the lines of the newer as compared with the older series.

(41) In folded strata the distinction between strike-faults and dip-faults is well marked. Fig. 32 shows an anticline, the arch of which is dropped down between two *strike-faults* ("trough-faulting"). In the sunken strip the boundary-lines are shifted inwards, and higher beds are thrown against lower. To obtain a rough estimate of the amount of throw, observe that the base of D is shifted, in the direction of strike, from *m* to *n* (800 ft.), while the slope in the same direction (*op*) is 100 in 1050, which gives a throw of about 76 ft. Note incidentally that in strata which are not folded (in the ordinary sense) there is sometimes a change of dip at a strike-fault. This is equivalent to folding of a simple type in addition to the faulting, and the throw should be estimated by the strike-method if that is applicable.

(42) For a *dip-fault* the shifting of the outcrops is very conspicuous. In an anticline the opposed outcrops are brought closer together on the downthrow side, and some of the lower beds are dropped out of sight; in a syncline the outcrops are thrown farther apart, and higher beds come in on the axis. Fig. 33 illustrates the latter case. It shows a sharp syncline, the steepest dip (at *fg*) being about 50 in 125, or 100 in 250 (nearly 22°). Note that in ordinary symmetrical folding (the axial plane being vertical) the axis is not shifted by a fault, and can therefore be laid down as in § 31. To measure the throw, draw the strike-line *abc*, and observe that the base of D is about 150 ft. higher on one side than on the other. Or, again, note that the top of E on one side is thrown against the base of D on the other, and the throw is therefore equal to the vertical

FIG. 32.

FIG. 33.

thickness of D + E, which is about 150 ft. as measured at *de* or *mn*.

(43) It is possible for faulting, as well as folding, to be renewed at a later period upon the old lines. Fig. 34 shows two unconformable series folded in an anticline and intersected by a dip-fault. The elevation of the anticline has been effected partly before and partly after the deposition of the newer series K, L, and the same is true of the movement of the fault. The proof is that the throw amounts to 100 ft. in the older rocks (*bc*), and only about 50 ft. in the newer (*de*).

(44) While a normal fault is related to lateral tension, and involves merely a relative subsidence as between the severed blocks, a *reversed fault* is a result of lateral thrust, and involves a piling up of the rocks on one side over those on the other. The hade is accordingly towards the upthrow side, and a pronounced hade is much more general here than in normal faulting. Fig. 35 illustrates a common case, in which a reversed fault has arisen as a further development of an overfold, the plane of fracture being in the under limb of the fold. The dip of the strata increases from the N.E. part of the map to the centre, where it culminates in a sharp anticline exposing the lowest beds (A). Just beyond this comes the fault, throwing higher beds on the S. side against lower on the N. Its hade is shown by its making a V (though a very blunt one) in crossing the valley, and the shape of its outcrop shows that it is scarcely steeper than the northern boundary of A. The relations are shown in fig. 36, a section taken along the line *mn*. It is clear that the "throw" of a fault of this kind, where the strata on the under side are nearly vertical, is not a term of any precise significance. The relative displacement of the rocks on opposite sides is the joint effect of the folding and the faulting, which were essentially successive stages of one process. In some areas of mountain-structure, such as the North-West Highlands of Scotland, there occur great reversed faults (*overthrusts*) with low inclination, often nearly horizontal.

FIG. 34.

FIG. 35.

The significant displacement in such a case is that in the horizontal direction, which amounts in some instances to many miles. As a result of such movements a newer formation may come to be overlain for some considerable distance by an older one, either inverted or in its natural posture. Subsequent folding will then affect both in common, the surface of overthrusting itself being thrown into folds.

(45) In general the relative displacement at a fault, whether normal or reversed, is wholly in the direction of hade, not horizontally along the fault. The observed lateral shifting of outcrops results from the vertical downthrow in conjunction with the dip of

FIG. 36.

the strata, and for vertical bedding there is no shifting. As an incident of overthrusting, however, there sometimes occurs a peculiar type of fault with real displacement in the horizontal direction as well as in the vertical (a *tear-fault* or *flaw*). Fig. 37 shows (diagrammatically on level ground) an anticline intersected by two such faults. It shows also a vertical dyke (X), the shifting of which affords a measure of the horizontal component of the displacement, being unaffected by the vertical throw. Beginning in the north, the first fault has a vertical throw of 100 ft. down to S. and a horizontal slide of 500 ft. to E. By the former the outcrops are shifted inward in accordance with their varying dips; by the latter they are all shifted through a constant distance to E. The resultant shift is everywhere eastward, but is greater in the western limb, where the two effects are additive, than in the eastern, where

they are subtractive. The second fault has the same vertical throw of 100 ft. to S., but a smaller horizontal slide of 250 ft. to E. This is not enough to counteract in the eastern limb the backward shift

FIG..37.

due to the throw down. Accordingly the resultant shift is inward for both limbs, but is greater in the western than in the eastern.

FIG. 38.

IV. STRATA WITH VARYING STRIKE.

(46) So far we have been able to assume, at least ideally, a constant strike in the strata, however they may have been tilted or folded. Casual irregularities, affecting strike as well as dip, do not call for notice here ; but we have now to examine certain cases in which *varying strike* is a necessary consequence of some special type of folding or faulting. Note that in this connection faulting can be regarded as merely an extreme case of folding, changes in dip (and strike) coming on abruptly instead of gradually. A normal fault is the analogue of a monoclinical fold, a reversed fault of an overfold (§ 44). Observe firstly that the strike necessarily varies *when a fold dies out* in the direction of its axis. Recalling that strike-lines are merely contour-lines on a bedding-surface, we can take fig. 2 above as representing the dying out of an anticline in horizontal bedding. The lines in the figure show the changing direction of strike, and their relative closeness corresponds with the relative steepness of dip at different places. On the axis there is a slight dip in the direction of the axis itself. [For a fold dying out in inclined strata there will be a more complex diagram, which the student may construct for himself.] An analogous case is that of a fault which dies out, or gradually changes in the amount of its downthrow.

(47) Consider next a *dome-like elevation*, such as is found in connection with certain types of igneous intrusion. For a dome rising from horizontal bedding the strike-diagram will be a system of concentric circles or ovals ; for a dome superposed upon a constant dip we may use fig. 4 above. It will serve as a key to fig. 38, which represents a dome due to a boss of granite G breaking through strata with a steady dip to S. This normal dip is seen in the marginal parts of the map. In the northern part it is opposed to the dip due to the dome, and there results a curved syncline, marked by the outlier

of D. On the south side of the dome the normal dip is augmented by that due to the elevation, and here the steepest dips are found. [Draw sections N.-S. and E.-W.]

(48) It is easy to see that folding on certain axes followed by a second folding on axes transverse to the former will give rise to a complicated arrangement of varying strike. For folding of a pronounced type strata of any rigidity do not in general behave in the fashion supposed, but yield rather by fracture and faulting. We sometimes find, however, folding with axes which are not horizontal, but have a certain inclination or *pitch*. [The definition of an axis as a line along which the bedding is horizontal therefore needs revision : it is a line where the dip is a minimum, and is directed along the axis itself.] This occurs not merely incidentally (§ 46), but affecting a system of anticlines and synclines. Fig. 39 is a strike-diagram for an anticline between two synclines, the axes having a steady pitch to north. It is to be taken as a key to fig. 40, a map constructed upon the same scheme. The inclination of the axes is manifest upon an examination of the map. Thus, *c* and *d* are points in the same bedding-plane and on the same synclinal axis, but from *c* to *d* there is a rise of about 45 ft. in 2450, indicating a pitch to N. of about 100 in 5500 (nearly 1°). There is a similar rise along *ab*. Note that *ef* and *gh*, on opposite sides of an anticlinal axis, converge northward ; while *ik* and *mn*, on opposite sides of synclinal axis, converge southward. [Compare throughout with fig. 39.]

(49) Concerning *igneous rocks*, as they figure on a geological map, a few words will suffice. Interbedded lava-flows, tuffs, etc., have the same relations as ordinary stratified formations, save that the thickness is likely to be more variable than is found in most types of sediments. In particular a coarse bedded agglomerate often thins out very rapidly in any direction away from its source. This behaviour may serve to indicate the situation of the source, and the exact place of the vent may be marked by a "volcanic neck" of agglomerate or a "plug" of intrusive rock. Among intrusions we

FIG. 39.

FIG. 40.

must distinguish two classes: the concordant, which (apart from irregularities) follow the direction of bedding in the strata invaded, and the transgressive, which systematically break across the bedding. Of the former, intrusive sills are often so regular in their habit, and so nearly constant in thickness, that they may be treated like ordinary stratified formations. In the case of a laccolite (or a phacolite among folded strata) the lenticular form is indicated by the outcrop, if erosion has cut through the whole thickness. If only the upper surface is exposed, there will be a doming effect apparent in the overlying strata, as in fig. 38. Note, however, that if G in that figure were a laccolite, its boundary (being really a bedding-surface) would run down into the heads of the small valleys. The smooth oval actually shown, disregarding the form of the ground-surface, implies a nearly vertical boundary. This is the sign of an intrusive boss, as equally of a volcanic plug or a "neck" of cylindrical form. In like manner a vertical dyke pursues its course indifferently across hill and valley. Only when there is a strong hade is the outcrop of a dyke influenced by the form of the ground, showing a blunt V where it crosses a valley. There remain the large subterranean intrusive bodies known as batholites, the true relations of which are only very partially displayed by a map. Such a body, as seen at its upper contact, often cuts obliquely across the strata, an effect indicated on the map by an apparent thinning out of a formation thus invaded.

(50) In conclusion, the object of these brief notes will have been attained if the student, in the first place, has acquired the habit of constantly visualising a geological map (whether contoured or not) in three dimensions; and if, secondly, he has effectively realised by practice that the interpretation of the details of structure as presented on a geological map is merely an application of elementary geometry. This is equally true whether the result can be worked out in precise terms or not. It is best illustrated by using, as we have done, large-scale contoured maps; but, when the point of view

has become instinctive, it may be brought to bear upon maps on which a larger tract of country is represented on a smaller scale. Above all, it must be realised that whatever information a geological map can convey is displayed on the face of the map, and is there to be read. The use of sections is to *illustrate* the relations so construed, and the student who draws sections in order to make out the geological structure will make little progress in the art of map-reading.

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Angle	Gradient 100 in	Sine	Cosine	Tangent
1°	5728	·017	1·000	·017
2	2864	·035	·999	·035
3	1908	·052	·999	·052
4	1430	·070	·998	·070
5	1143	·087	·996	·087
6	951	·105	·995	·105
7	814	·122	·993	·123
8	712	·139	·990	·141
9	631	·156	·988	·158
10	567	·174	·984	·176
11	514	·190	·982	·194
12	470	·208	·978	·213
13	433	·225	·974	·231
14	401	·242	·970	·249
15	373	·259	·966	·268
16	349	·276	·961	·287
17	327	·292	·956	·306
18	308	·309	·951	·325
19	290	·326	·946	·344
20	275	·342	·940	·364
21	260	·359	·934	·384
22	248	·375	·927	·404
23	236	·391	·920	·424
24	225	·407	·914	·445
25	214	·423	·906	·466
26	205	·438	·899	·488
27	196	·454	·891	·510
28	188	·469	·883	·532
29	180	·485	·875	·554
30	173	·500	·866	·577
32	160	·530	·848	·625
34	148	·559	·829	·675
36	138	·588	·809	·727
38	128	·616	·788	·781
40	119	·643	·766	·839

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